FREEDOM

Advanced Development Program

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ECLSS Predictive Monitoring

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Space Station Evolution:
Beyond the Baseline
League City, Texas
August 8, 1991

JPL

N92-17357

TITLE

ECLSS Predictive Monitoring: Automated Evaluation of Sensor Placements

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The trend for many years as space platforms have become more complex has been to oversense these systems, to anticipate unforeseen fault modes and sensor failures. However, this strategy becomes untenable when the amount of sensor data becomes too great for operators to assimilate and interpret, and when the cost, launch weight, and power consumption of too many sensors becomes unacceptable.

On Space Station Freedom (SSF), design iterations have made clear the need to keep the sensor complement small. Along with the unprecedented duration of the mission, it is imperative that decisions regarding placement of sensors be carefully examined and justified during the design phase.

In the ECLSS Predictive Monitoring task, we are developing AI-based software to enable design engineers to evaluate alternate sensor configurations. Based on techniques from model-based reasoning and information theory, the software tool makes explicit the quantitative tradeoffs among competing sensor placements, and helps designers explore and justify placement decisions. This work is being applied to the Environmental Control and Life Support System (ECLSS) testbed at MSFC to assist design personnel in placing sensors for test purposes to evaluate baseline configurations and ultimately to select advanced life support system technologies for evolutionary SSF.

BACKGROUND

JPL is conducting research on advanced monitoring systems which maximize feedback of engineering information from complex, dynamic space systems where human and computational resources are constrained. This work has impact upon both real-time monitoring (sensor selection) and system design (sensor placement).

MSFC and Boeing contractors are working on fault detection, isolation, and recovery (FDIR) for SSF ECLSS and are performing tests on and evaluating designs for SSF ECLSS hardware.

The ECLSS Predictive Monitoring task will transfer results on real-time monitoring capabilities and sensor placement guidance from work on the SELMON system at JPL to MSFC to support ECLSS testbed activities addressing SSF baseline and evolutionary requirements.

BACKGROUND

JPL:
research on monitoring and monitorability of complex, dynamic space systems

MSFC and Boeing:
FDIR and design evaluation for SSF ECLSS

ECLSS Predictive Monitoring task
sensor placement guidance during system design and sensor selection for real-time monitoring

PROBLEM

Sensor placement is the task of determining a set of sensors which allows the most accurate, safe, and reliable determination of the overall state of a monitored system while minimizing sensor power consumption, cost, computing power requirements, and weight. Reducing these quantities is particularly important in space-borne systems due to power and payload restrictions. In complex systems, this minimization task can be quite difficult.

PROBLEM

Sensor placement is the task of determining a set of sensors which allows an accurate determination of the overall state of the system while minimizing:

- power consumption
- cost ($$)
- computing power requirements
- launch weight

for space-borne systems (SSF), minimization is crucial

in complex systems (SSF ECLSS), minimization is difficult

OBJECTIVE

The objective of this project is twofold: Current work is aimed at providing ECLSS design engineers with software tools for evaluating alternative baseline SSF sensor placements. More specifically, to assist ECLSS designers in verifying that proposed baseline sensor configurations ensure safe, reliable monitoring while minimizing power, weight, computing requirements, and monetary cost. For evolutionary SSF, automated sensor placement will facilitate the utilization of advanced life support technologies (e.g. closed-loop regenerative life support) with more complex monitoring requirements which were unacceptable for baseline ECLSS because the monitoring requirements could not be easily met with available techniques.

OBJECTIVE

Baseline: Facilitate minimization of sensors while maintaining safe, reliable monitoring

Evolutionary: Enable utilization of more advanced technologies while maintaining monitorability

BENEFITS

Our approach uses a model-based simulation capability to evaluate how each sensor rates with respect to several monitorability measures over the behavior space of the monitored system. These scores can then be used to evaluate a proposed sensor configuration.

This sensor placement evaluation capability provides a number of benefits. First, this evaluation capability will aid designers in the sensor placement task by facilitating evaluation of alternative sensor placements. In particular, this capability would provide a quantitative measure of tradeoffs in sensor placements which previously have been viewed only subjectively. A second benefit is that quantification of sensor placement measures will aid in design documentation by allowing quantitative justification for sensor placements. Third, the automated evaluation capability will facilitate assessment of the impact of system design changes upon sensor placements. Finally, as a fourth benefit, this sensor placement evaluation capability can be used to aid in sensor power planning. When the utility of a sensor depends greatly upon the operating mode of the monitored device, it may be possible to reduce overall sensor power consumption by powering certain sensor suites only in limited operating modes. Because our approach measures the utility of sensors in each system operating mode, it can assist in sensor power planning.

BENEFITS

- Facilitates evaluation of alternative sensor placements.
- Provides a quantitative measure of tradeoffs.
- Supports design documentation.
- Facilitates assessment of impact of design changes.
- Facilitates sensor power planning.

MODEL-BASED APPROACH

Our approach to sensor placement can be described generally as follows:

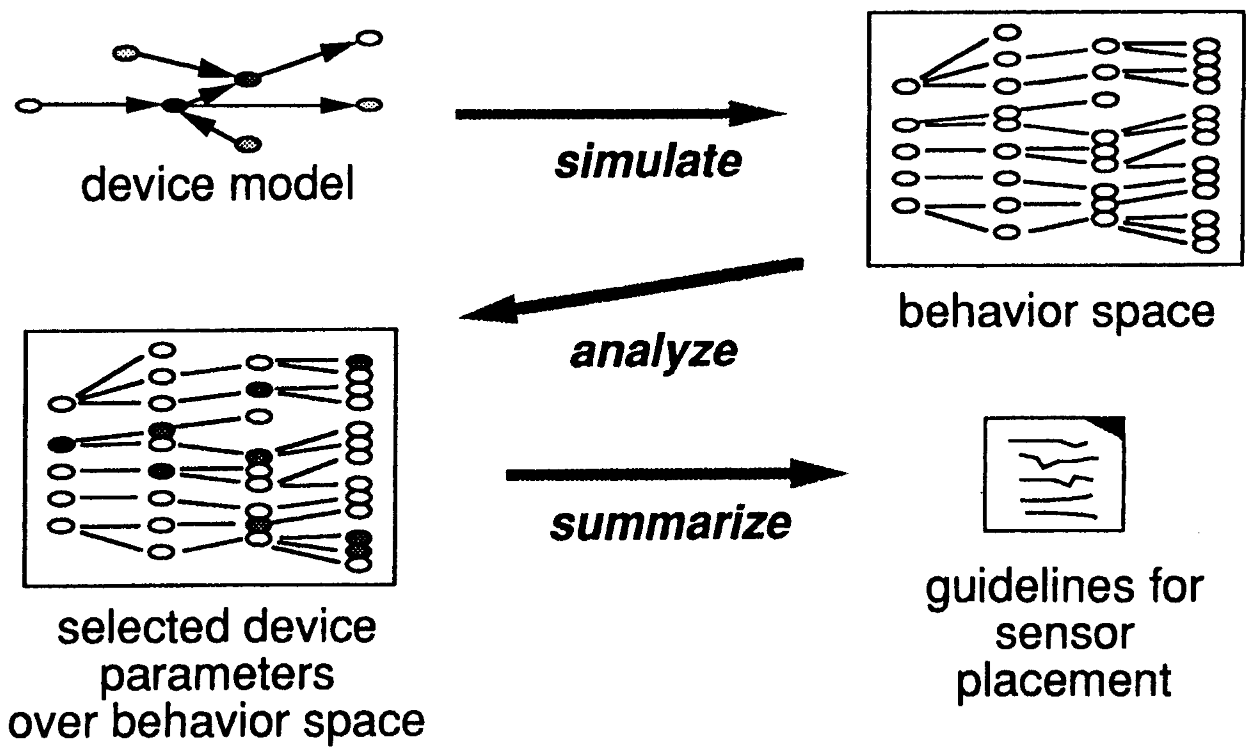
1. Given nominal behavioral models of the system and a causal simulation capability, generate a behavior space for the system.

2. Apply monitorability measures for sensitivity, cascading alarms, and potential damage to simulated system operation over these operating modes.

3. Compute teleological analysis scores.

4. Compute sensor placement recommendations as those with highest scores from the analyses.

MODEL-BASED APPROACH



MONITORABILITY MEASURES

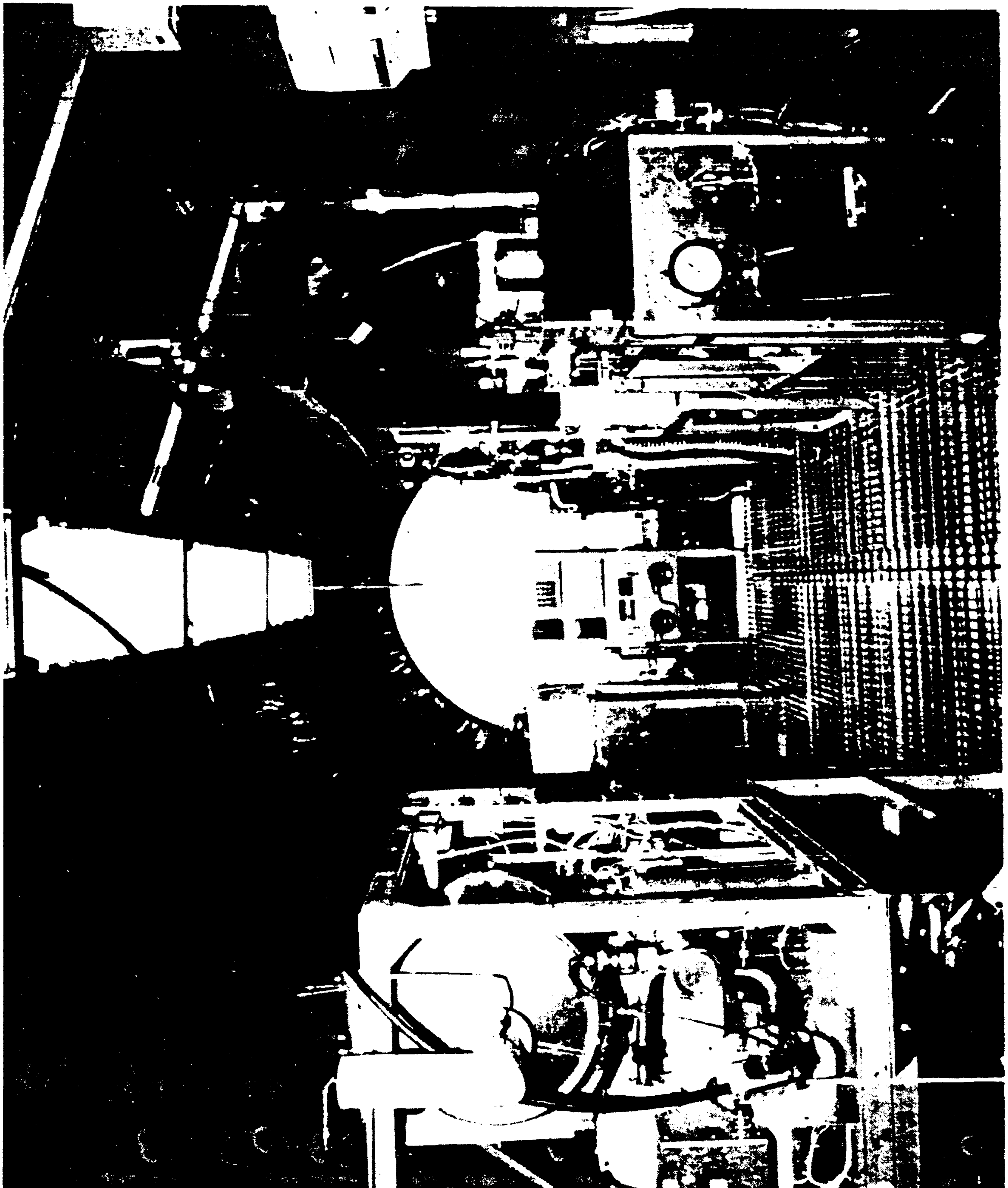
Our model-based reasoning approach to evaluating sensor placements uses four monitorability measures. *Sensitivity Analysis* suggests sensor placements which measure quantities which have the greatest impact upon the overall state of the system. *Cascading Alarm Analysis* suggests sensor placements which measure quantities whose changes have the potential to generate many alarms. *Potential Damage Analysis* suggests those sensor placements which measure quantities which are likely to cause permanent damage to devices in the system being monitored. *Teleological Analysis* suggests sensor placements which monitor quantities relevant to specified operational goals of the system. Our approach uses a model-based simulation capability to evaluate how each sensor rates with respect to each of these measures over the behavioral space of the monitored system. These scores can then be used to generate a proposed sensor set.

MONITORABILITY MEASURES

- Sensitivity analysis
- Cascading Alarms analysis
- Potential Damage analysis
- Teleological analysis

THE SSF ECLSS TESTBED AT MSFC

Our sensor placement approach is being tested upon the water reclamation subsystem of the Environmental Control and Life Support System (ECLSS) for Space Station Freedom. A model describing the behavior of the multifiltration (MF) subsystem in terms of fluid flow and heat transfer has been constructed. This model was developed via a combination of study of design documentation (i.e. schematics, etc.) and consultation with domain experts (e.g. the operators of the testbed). This model has been validated by comparison against actual data from the subsystem testbed undergoing evaluation at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. We are in the process of extending our model to cover more of the ECLSS subsystems, including the air recycling subsystem.



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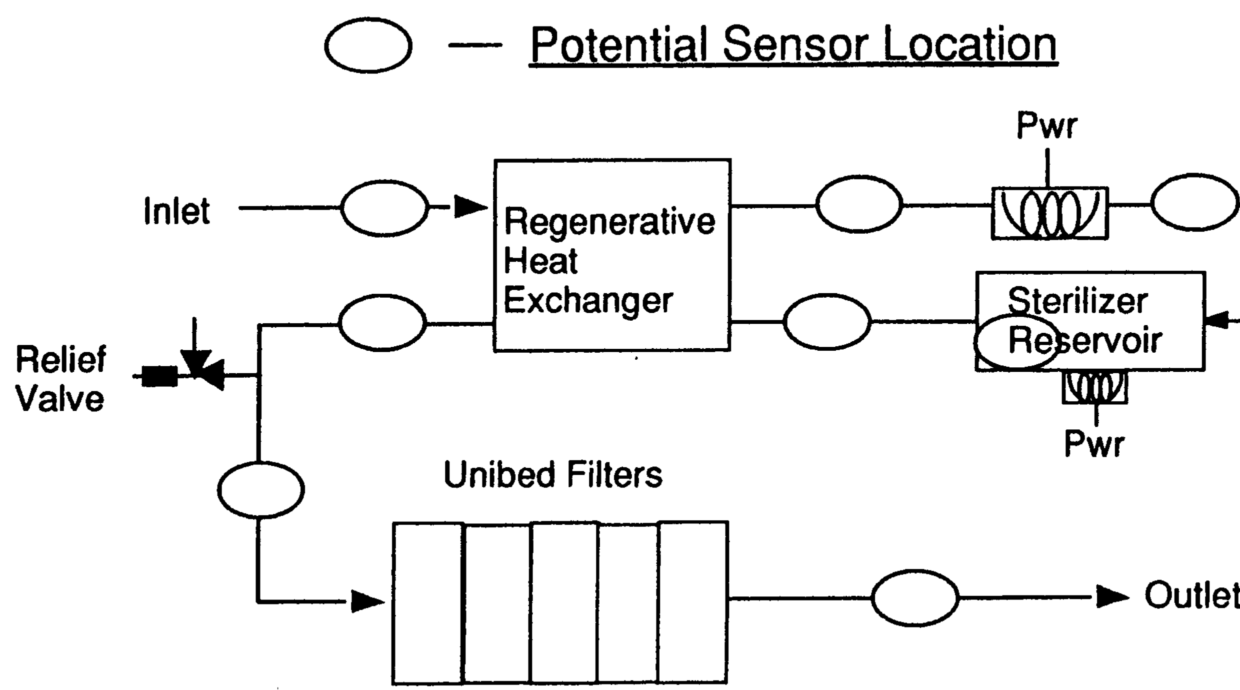
THE MULTIFILTRATION SUBSYSTEM

The ECLSS multifiltration (MF) subsystem consists of two parts -- the sterilization loop and the unibed assembly. In this subsystem, the water first passes through a pump at the inlet to the system. Next, the water passes through a coarse filter before entering the sterilization loop. In the sterilization loop the water is heated in the regenerative heat exchanger and then by the in-line heater. The in-line heater has only a coarse temperature control and thus the water temperature here may differ by as much as 10° F from the goal of 250° F. Within the sterilizer reservoir, the temperature of the water is maintained more accurately at 250°F for about 9 minutes. In the second portion of the subsystem, the water passes through a set of unibed filters designed to remove particulate contaminants from the water. Possible sensor types are flow rate, water pressure, and temperature. Possible sensor locations are indicated in by ovals.

Specified operational goals are:

1. maintain processed water at 250°F in sterilizer reservoir for 9 minutes; and
2. maintain water flow through the unibed of at least 15 mL/minute.

MULTIFILTRATION SUBSYSTEM



SENSITIVITY ANALYSIS

Sensitivity Analysis measures the sensitivity of other quantities in the monitored system to changes in a given quantity. This measure depends upon information about "normal" magnitudes of change for the devices in question. For each normal operating mode of the system, the following procedure is followed. For each quantity $Q \in$ MonitorableQuantities (the set of all monitorable quantities in the model), determine nominal operating values and alarm ranges. Next compute a normalized change increase $\Delta Q+$ and decrease $\Delta Q-$ as the average amount of change between updates for that operating mode. Next, for each quantity Q, beginning with an initial state where all devices/sensors are at nominal operating values, simulate a change ΔQ in Q, propagating this change to other quantities in AllQuantities (the set of all quantities in the model), as dictated by the model. For each such changed quantity Q' $\in$ AllQuantities, for each time the quantity changes during the simulation, collect a sensitivity score proportional to the amount of change in Q' from its normal value $Q'_{nominal}$ relative to alarm thresholds but also modified by a decreasing function of time[1]. This calculation captures the notion that delayed and less direct effects are more likely to be controllable and less likely to occur. Thus, a change which affects a quantity Q' but occurs slowly is considered less important. This simulation proceeds for a preset amount of simulated time. Then, for each changed quantity Q', take the maximum of the collected change score for that quantity. The sensitivity score for Q is the sum of these maximums for all the Q's. Thus, for each quantity Q, a simulated change produces a set of changescores for other quantities in the model. The sensitivity score for Q is the sum of the respective maximums of each of these sets[2]. The computation of the sensitivity scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default).

For each change to a quantity Q' occurring at time T_{change}, compute a change score as follows.

let Q'_{new} be the new value for Q'

$$\text{changescore}(Q') = \frac{|Q'_{new} - Q'_{nominal}|}{|Q'_{alarm} - Q'_{nominal}|} \bullet \frac{(\Delta T - T_{change})}{\Delta T}$$

add this changescore to the set of collected changescores for Q'

let MaxChangeScore(Q') = the maximum of the set of collected changescores for Q'

$$\text{let sensitivity}(Q) = \sum_{Q' \in \text{AllQuantities}} \text{MaxChangeScore}(Q')$$

The overall sensitivity score for Q is then computed by summing the sensitivity scores for $\Delta Q+$ and $\Delta Q-$ weighted by relative frequency of increase vs. decrease for Q.

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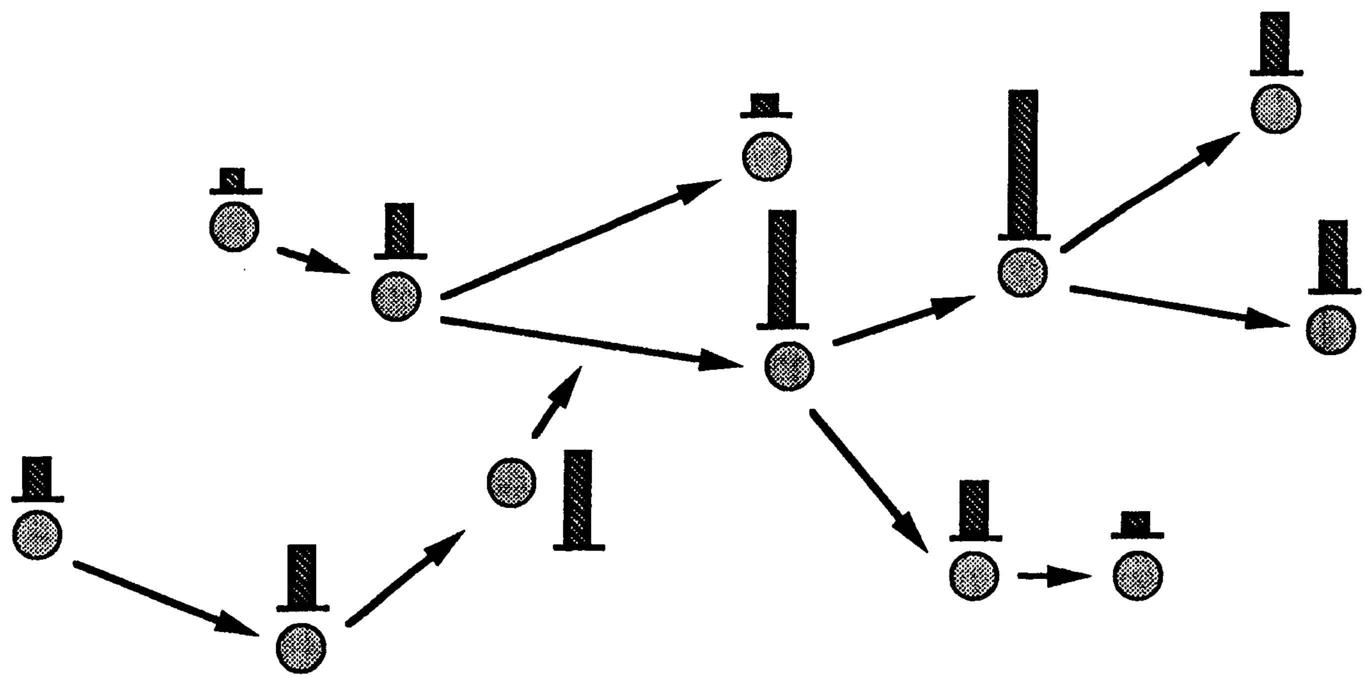
[1]This can be viewed as an average $\partial Q'/\partial Q$ modified by a decreasing function of time elapsed and normalized for the alarm threshold for Q'.

[2]Quantities which do not change when Q is changed produce an empty set of changescores. We define the maximum of this empty set as 0 for the purpose of the sensitivity summation.

SENSITIVITY ANALYSIS

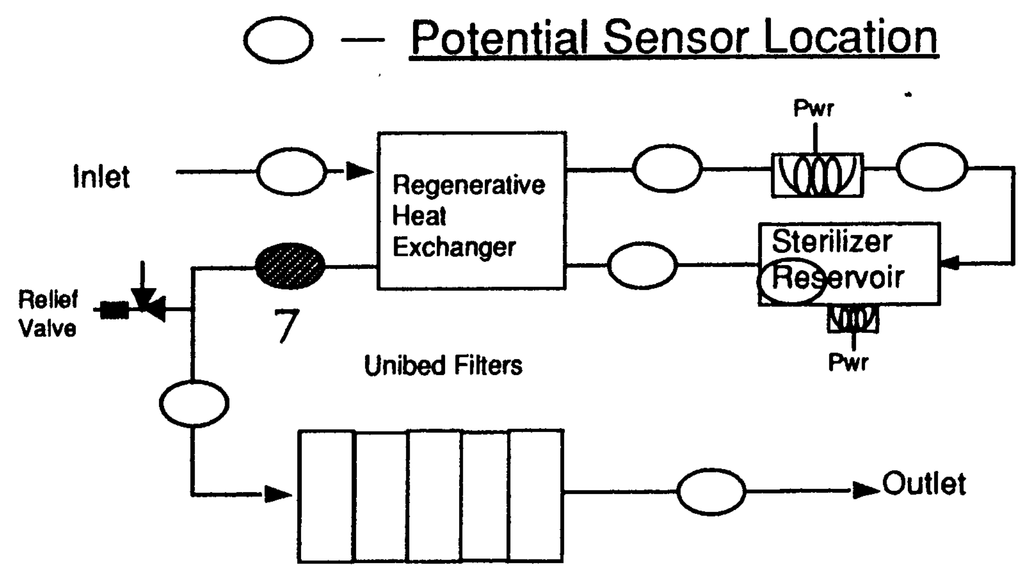


identify those sensors which, when undergoing change, result in the greatest global change within the system

SENSITIVITY RECOMMENDATIONS

Sensitivity Analysis suggests the specific placement of a pressure sensor near the relief valve at point 7. This is because the relief valve is pressure controlled; if the pressure at point 7 is above 40 psig, the relief valve will open and drastically change the system behavior. The opening of the relief valve would cause an immediate significant pressure loss, as well as significantly affecting flow in the MF subsystem.

SENSITIVITY RECOMMENDATIONS



recommend pressure sensor at point 7 because pressure there affects the operation of the relief valve, which significantly affects overall system operation

CASCADING ALARMS ANALYSIS

Cascading alarms analysis measures the potential for change in a single quantity to cause a large number of alarm states to occur, thus causing information overload and confusion for operators. As with sensitivity analysis, cascading alarms analysis is performed for each operating mode of the monitored system. For a standardized amount of increase and decrease for each monitorable quantity Q, the effects of such a change are propagated throughout the system and the number of triggered alarms is counted. This standardized amount of change is different from the measure used in the sensitivity analysis as normal changes are not likely to produce cascading alarm patterns. The alarm count is then normalized for the total number of possible alarms. The weight of each alarm state triggered is also decreased as a function of the time delay from the initial change event to the alarm. This has the effect of focusing this measure on quickly developing cascading alarm sequences which are the most difficult to interpret and diagnose. The computation of cascading alarms scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default) where $\Delta Q+$ and $\Delta Q-$ are functions of the distance between the nominal value for Q and the alarm value for Q in the increasing and decreasing directions respectively

$$\text{let CascadingAlarm}(Q) = \frac{\sum_{Q' \in \text{all quantities}} \text{InAlarm}(Q')}{\text{number of quantities } Q'}$$

where $\text{InAlarm}(Q') = (\Delta T - T_{alarm})/\Delta T$

if Q' entered an alarm range during the simulation and T_{alarm} is the earliest time Q' was in an alarm range

and

$\text{InAlarm}(Q') = 0$

if Q' did not enter an alarm range during the simulation.

JPL

Advanced Development Program

ECLSS Predictive Monitoring

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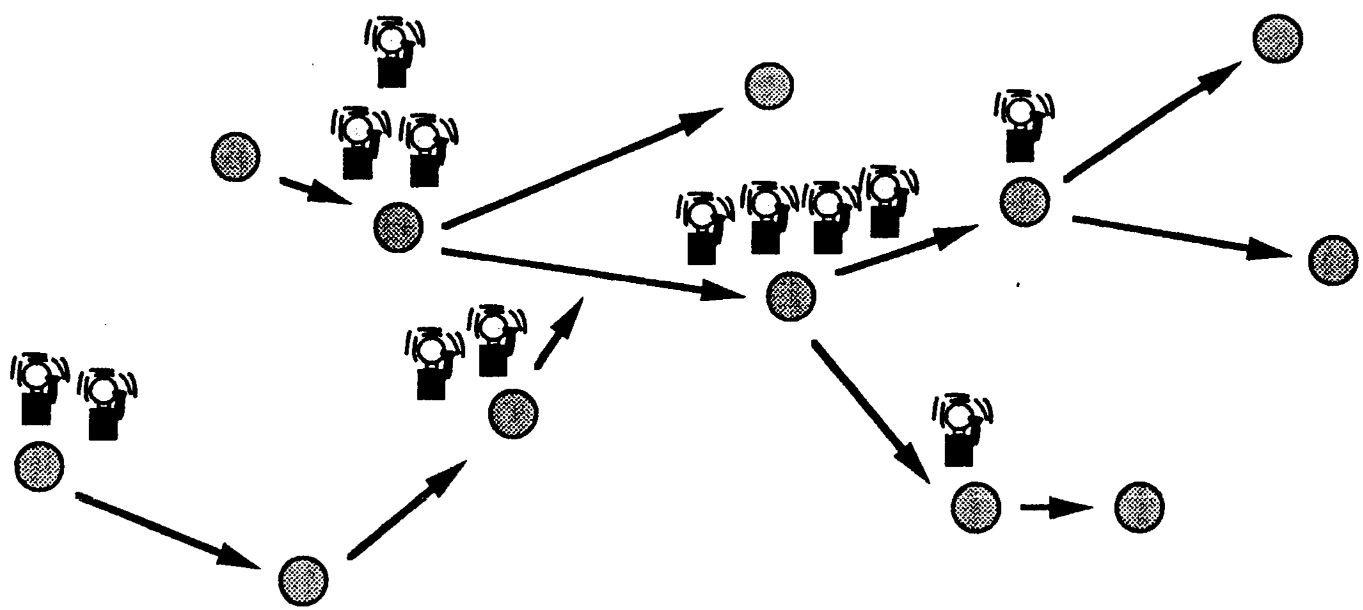
CASCADING ALARMS ANALYSIS

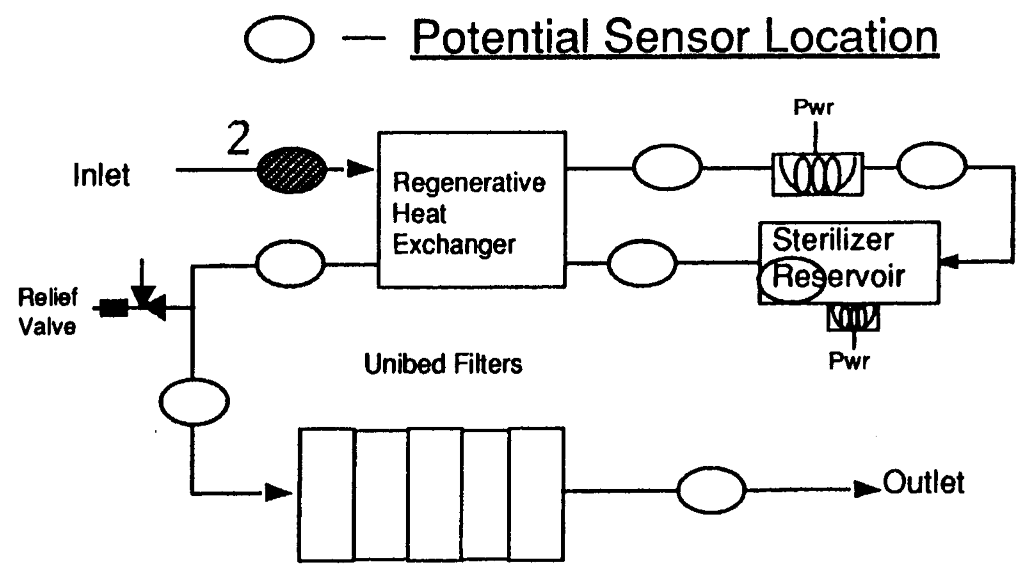


identify those sensors which, when in alarm, have the greatest potential to create alarm states elsewhere in the system

CASCADING ALARMS RECOMMENDATIONS

Cascading alarms analysis suggests placement of flow rate sensors because significant perturbations in flow rate can cause cascading temperature and pressure alarms.

CASCADE RECOMMENDATIONS



recommend flow sensor at point 2 because anomalous flow can cause cascading pressure and temperature alarms

POTENTIAL DAMAGE ANALYSIS

Another measure is potential damage analysis, which is computed in two parts -- predictive potential damage and potential damage detection. Predictive potential damage measures the capability of a sensor to predict damage to devices in the system. For each device and quantity associated with that device, there is an associated operating range which is judged to be harmful to the device. Predictive potential damage analysis is performed by simulating a change in each monitorable quantity Q and scoring upon the basis of how many devices will enter harmful ranges due to the change in Q. Predictive potential damage analysis scores are moderated by the number of control points which may interdict the damage. For the causal path leading to the damaged device, for each mechanism (arc in the causal graph) which can be influenced by a controllable parameter, the potential damage score is reduced. The potential damage measure depends more critically upon domain-specific information beyond the schematic, as many of the potential damage scenarios involve device or subsystem interactions. The computation of potential damage scores is shown below.

Simulate a change $\Delta Q+$ or $\Delta Q-$ to Q beginning at time 0 and continuing to time ΔT (a user-supplied default).

$$\text{let PotentialDamagePredict}(Q) = \sum_{Q' \in \text{all quantities}} \text{Damaged?}(Q')$$

where

$$\text{Damaged?}(Q') = \frac{(\Delta T - T_{alarm})}{\Delta T \times (\text{control} + 1)}$$

if Q' entered a damaging range during the simulation where T_{alarm} is the earliest time Q' was in a damage range and control is the number of control points in the causal chain leading to the damaging quantity value and

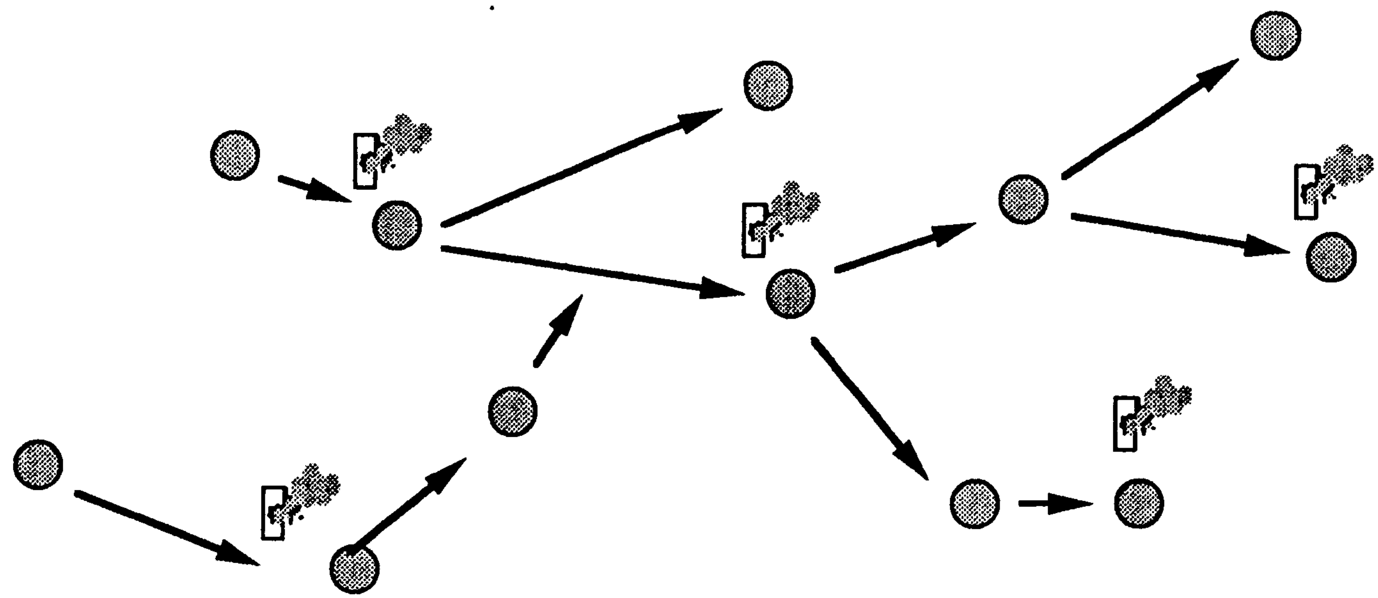
$$\text{Damaged?}(Q') = 0$$

if Q' did not enter a damage range during the simulation.

The second part of potential damage analysis is damage detection. In this measure, the model is used to simulate devices in the system entering damaging operating modes, and potential sensors are scored upon the basis of how much they change (in the same manner as the sensitivity analysis). Damage detection analysis is performed by propagating a change resulting in a device entering a damaging range, and measuring the resulting change in other sensors as in sensitivity analysis. Those sensors which change more significantly to indicate the damaging device state are scored higher by the damage detection analysis. Let $\Delta Q'+$ or $\Delta Q'-$ be changes sufficient to cause Q' to enter a device damaging range. Simulate a change $\Delta Q'+$ or $\Delta Q'-$ to Q' beginning at time 0 and continuing to time ΔT (a user-supplied default).

$$\text{let PotentialDamageDetect}(Q) = \sum_{Q' \in \text{all quantities}} \text{Changescore}(Q)$$

POTENTIAL DAMAGE ANALYSIS

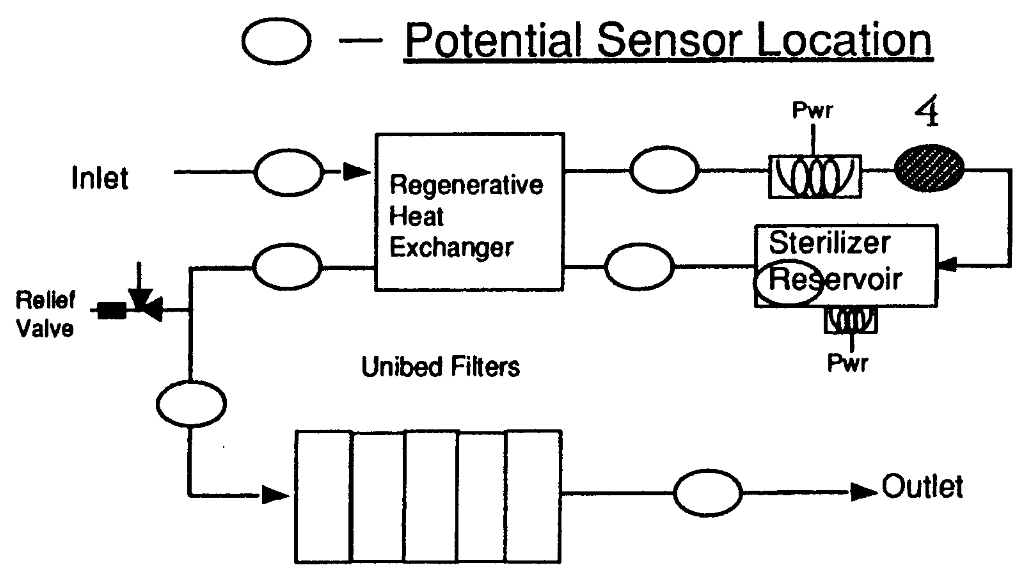


identify those sensors which predict or inform of permanent damage to the system

POTENTIAL DAMAGE RECOMMENDATIONS

Potential Damage Detection Analysis suggests placing a temperature sensor at point 4. If the in-line heater overheats, it could cause the water flowing through to be raised to an unacceptably higher temperature than normal.

DAMAGE RECOMMENDATIONS



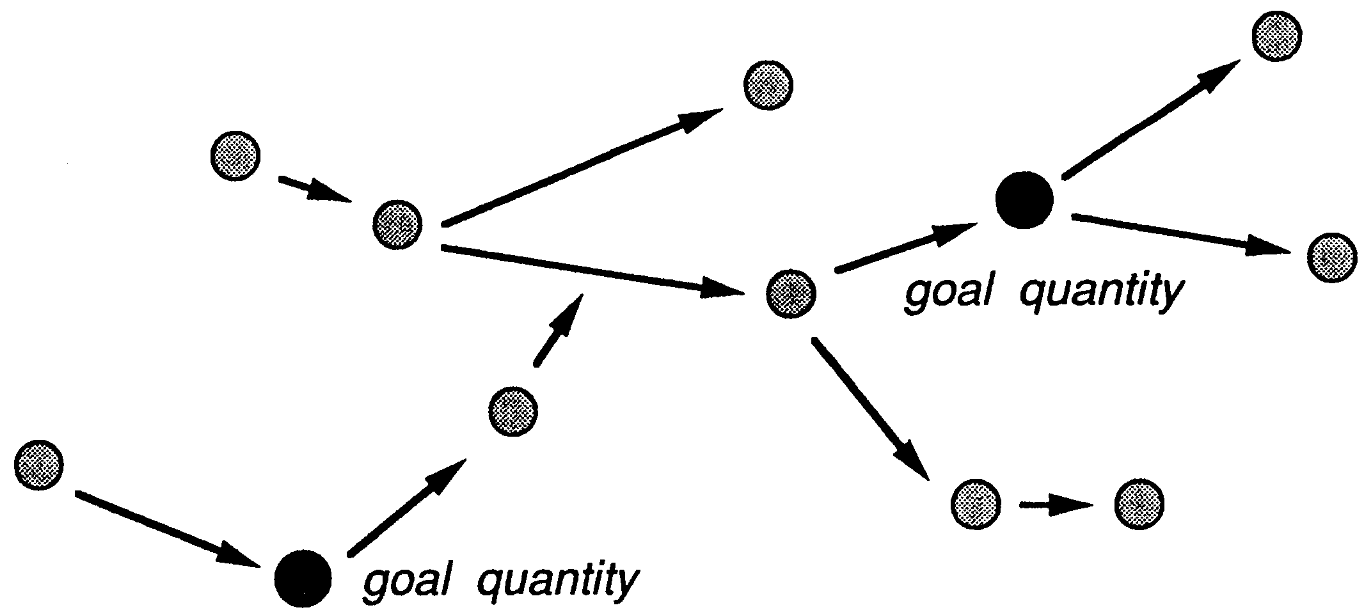
recommends temperature sensor at point 4 to detect a damaging overheating of the in-line heater immediately upstream

TELEOLOGICAL ANALYSIS

The final measure is teleological analysis, which does not use the model-based simulation capability. Instead, teleological analysis directly examines mechanism dependencies in the causal graph to produce a sensor placement score.

Teleological analysis suggests measurements of quantities which provide the most direct feedback on operational goals of the system being monitored. In this measure, those quantities directly mentioned in the operational specifications of the system are scored highest, those quantities directly influencing these quantities are scored next highest, etc. The exact computation of the teleological measure involves backtracing the causal graph. Directly monitorable quantities appearing in the goal description receive a score of 1. For each mechanism affecting the goal quantity, a teleology score inversely proportional to the number of such mechanisms is divided equally among the inputs to the mechanism. Thus, if there are m mechanisms affecting a goal quantity, and one of these mechanisms has n inputs, each such input receives a score $1/mn$. Note that multiple independent causal influence paths combine additively. While this process proceeds recursively for mechanisms potentially influencing the inputs to the given mechanism, each level is multiplied by $1/d$ where d is the number of mechanisms (arcs in the causal graph) distant from the goal quantity.

TELEOLOGICAL ANALYSIS

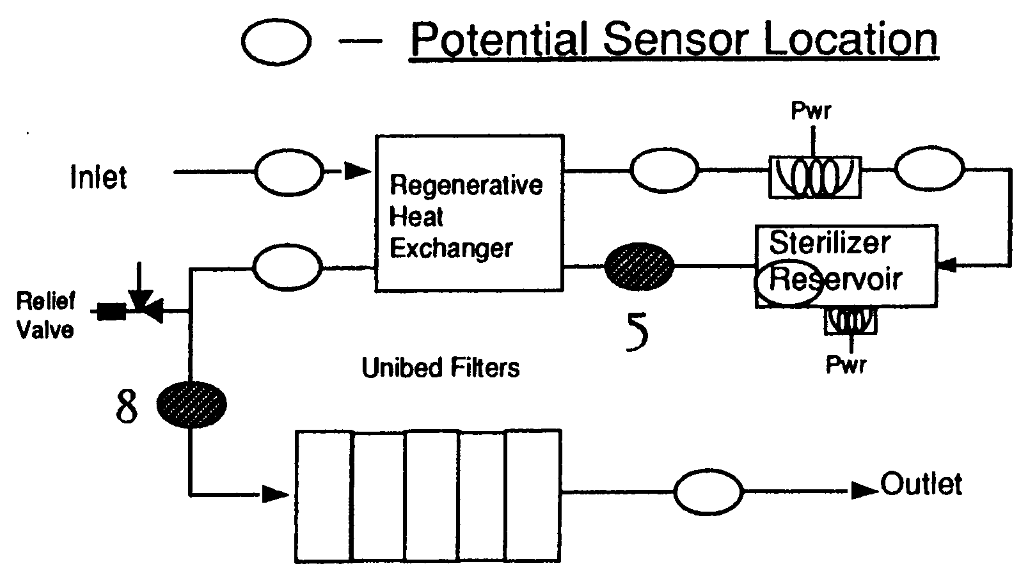


identify those sensors which correspond to quantities most directly related to operational goals of the system

TELEOLOGICAL RECOMMENDATIONS

Teleological Analysis suggests placing flow rate sensors at point 8 to verify the flow of water through the unibeds as the flow rate is directly mentioned in the operational goal specification. Teleological Analysis also scores highly a flow rate sensor in the sterilizer reservoir (point 5), as this quantity determines the time spent by the water in the sterilizer reservoir. Finally, Teleological Analysis suggests placement of a temperature sensor for the sterilizer reservoir (point 5), as this quantity appears in the operational goal specification of the system.

TELEOLOGICAL RECOMMENDATIONS



recommends temperature and flow sensor at point 5 because of the temperature and time goals of the sterilizer reservoir; recommends a flow sensor at point 8 because of the unibed flow goal

COLLABORATION

JPL and MSFC personnel are collaborating in the ECLSS Predictive Monitoring Task. JPL personnel are developing information quantification and model-based reasoning techniques applicable to both sensor placement for monitorability and sensor selection in monitoring. In support of these goals, MSFC personnel are assisting by providing technical expertise to support the construction of models of ECLSS subsystems. Additionally, MSFC personnel are providing ECLSS testbed data to be used in testing the sensor placement and sensor selection software being developed at JPL. As results from this testing become available, they are made available to MSFC personnel who provide feedback on the value and accuracy of sensor placement and sensor selection recommendations. This feedback is used to refine the methods and software being developed at JPL.

JPL/MSFC COLLABORATION

JPL

sensor placement capability to support ECLSS design

sensor selection capability to support ECLSS monitoring

ECLSS test data to drive research

feedback from domain experts on sensor recommendations for ECLSS

MSFC

SCHEDULE

The first users of the sensor placement evaluation and generation capabilities developed in this task will be the MSFC ECLSS design team led by Environmental Control and Life Support Branch Chief K. Mitchell.

FY91: The design for the sensor placement evaluation tool based on four monitorability measures has been completed. A proof-of-concept[3] demonstration will be completed for the SSF ECLSS MF subsystem. Causal modelling efforts have been targeted for the water reclamation subsystem of ECLSS.

FY92: The proof-of-concept sensor placement tool based on monitorability measures will be extended to a functional prototype system. This full-capability system will be available for evaluating proposed baseline ECLSS sensor configurations. Although the delivery date for this system will miss the POST milestone for the air side of ECLSS, it will precede the POST milestone for the water side of ECLSS by 6 months, the POST milestone for integrated ECLSS subsystems by 12 months, and the first BOST deadline for ECLSS (air side) by ~18 months. Also, in FY92, a design and proof-of-concept demonstration for a sensor placement evaluation tool based on diagnosability measures will be completed. Causal modelling efforts on the water reclamation subsystem of ECLSS will be completed and modelling efforts on the air recycling subsystem will be initiated. A design for a sensor placement generation tool also will be developed.

FY93: The functional prototype sensor placement tool based on monitorability measures will be extended to a pilot system. The proof-of-concept sensor placement tool based on diagnosability measures will be extended to a functional prototype system. This full-capability system will be available for evaluating proposed baseline ECLSS sensor configurations. Although the delivery date for this system will miss the POST milestone for the air side of ECLSS and coincide with the POST milestone for the water side of ECLSS, it will precede the POST milestone for integrated ECLSS subsystems by 6 months, and the first BOST deadline for ECLSS (air side) by ~12 months. Also in FY93, causal modelling efforts on the air recycling subsystem will be completed. A proof-of-concept demonstration for a sensor placement generation tool will be completed.

FY94 & FY95: The functional prototype sensor placement tool based on diagnosability measures will be extended to a pilot system. Both pilot sensor placement evaluation tools will be available for evaluating monitoring and diagnosis requirements for advanced life support technologies for evolutionary SSF. The proof-of-concept system for a sensor placement generation tool will be extended to a functional prototype system. Sensor configurations obtained with this software tool will be available for evaluation. In FY95, the functional prototype system for a sensor placement generation tool will be extended to a pilot system.

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[3] A proof-of-concept (POC) system is one which works correctly on a specific example or set of examples but is not designed to be robust and extendable. A functional prototype system is one which provides full capability, is robust and extendable, and is delivered both for actual use and for rigorous testing and evaluation in a real setting. A pilot system is one which has been refined through feedback provided on the functional prototype system and is delivered for general use with stated and frozen design specifications.

SCHEDULE

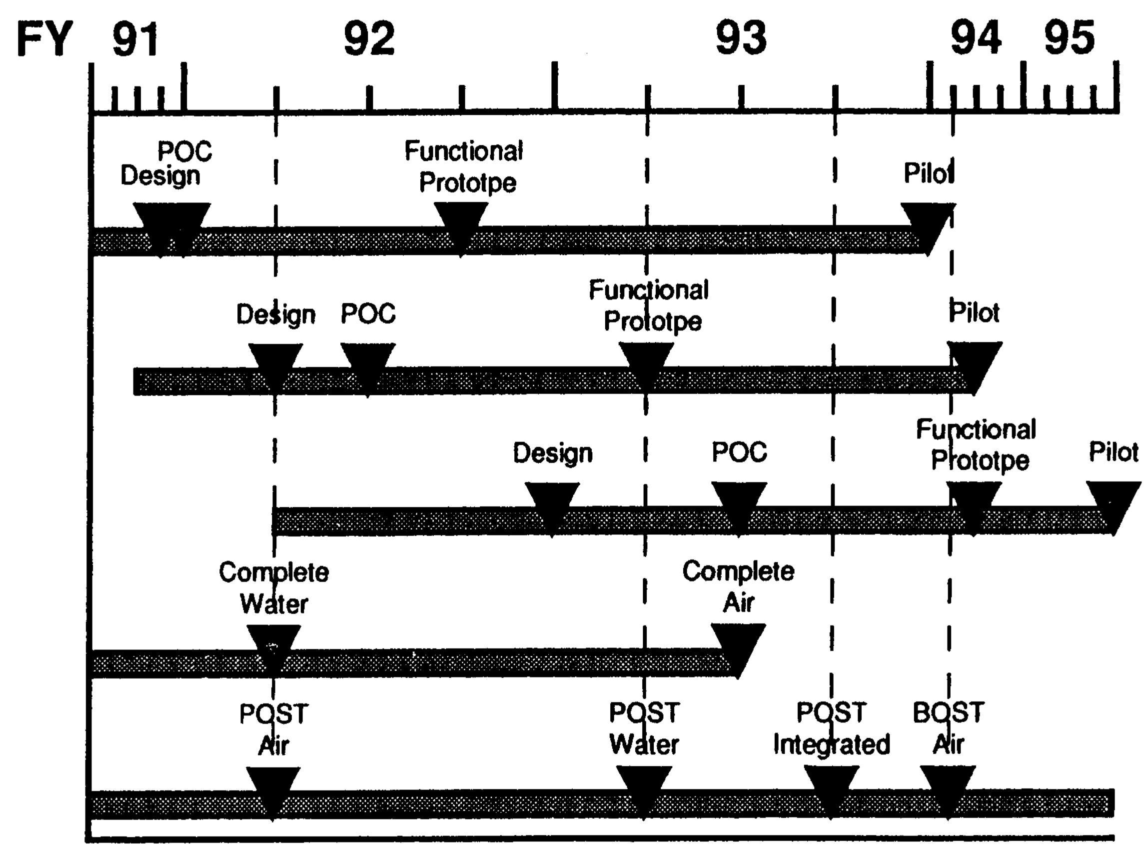
Develop sensor placement evaluation capability for monitorability measures

Develop sensor placement evaluation capability for diagnosability measures

Develop sensor placement generation capability

Develop causal models of ECLSS subsystems

MSFC ECLSS Testbed Operational Systems Testing



SUMMARY

The trend for many years as space platforms have become more complex has been to oversense these systems, to anticipate unforeseen fault modes and sensor failures. However, this strategy becomes untenable when the amount of sensor data becomes too great for operators to assimilate and interpret, and when the cost, launch weight, and power consumption of too many sensors becomes unacceptable.

On Space Station Freedom (SSF), design iterations have made clear the need to keep the sensor complement small. Along with the unprecedented duration of the mission, it is imperative that decisions regarding placement of sensors be carefully examined and justified during the design phase.

In the ECLSS Predictive Monitoring task, we are developing AI-based software to enable design engineers to evaluate alternate sensor configurations. Based on techniques from model-based reasoning and information theory, the software tool makes explicit the quantitative tradeoffs among competing sensor placements, and helps designers explore and justify placement decisions. This work is being applied to the Environmental Control and Life Support System (ECLSS) testbed at MSFC to assist design personnel in placing sensors for test purposes to evaluate baseline configurations and ultimately to select advanced life support system technologies for evolutionary SSF.

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

We would like to thank Jay Wyatt of Marshall Space Flight Center for innumerable discussions regarding the operation of the ECLSS water reclamation subsystem.

For further information see:

S. A. Chien, R. J. Doyle, and L. S. Homem de Mello, "A Model-based Reasoning Approach to Sensor Placement for Monitorability," *Space Operations, Applications, and Research Symposium*, Houston, July 1991. Also appears in the *Proceedings of the Workshop on Model-Based Reasoning, 9th National Conference on Artificial Intelligence*, Anaheim, July 1991.

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R. J. Doyle, S. M. Sellers, and D. J. Atkinson, "A Focused, Context-Sensitive Approach to Monitoring," *11th International Joint Conference on Artificial Intelligence*, Detroit, August 1989.

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SUMMARY

- Trend has been to oversense systems to be monitored.

- SSF sensor complement must be small.
- Constrained by cost($$), launch weight, power consumption, computing requirements.
- Must maintain safe, reliable monitoring.

- JPL is developing an AI-based tool to assist design engineers in evaluating alternative sensor placements.
- Being applied to evaluation of alternate baseline SSF ECLSS sensor configurations.
- Will be applied to ensure monitorability of advanced life support technologies for evolutionary SSF.